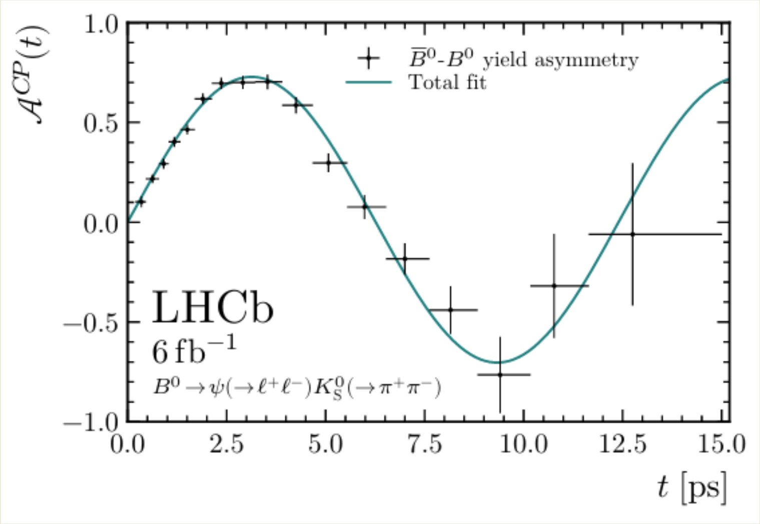
$B_q \to J/\psi\, K, B_q \to J/\psi\pi$



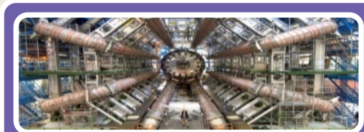
FCC CPV WG

31 March 2026

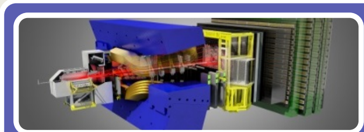
Yossi Nir
Weizmann Institute

Why Flavor & CPV?

Flavor violation and CPV probe otherwise uncharted territory: $10 - 10^4$ TeV

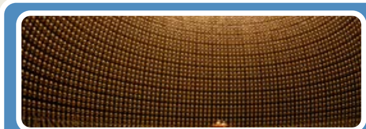


FV and CPV probe otherwise uncharted territory of d=6 SMEFT operators



FCC-ee will provide unprecedented huge statistics

FCC-ee will provide unprecedented low background



FCC-ee will provide unique tagging capabilities

FCC-ee has a guaranteed, rich, unique, exciting flavor and CPV program

$B_q \to J/\psi\, P$: based on

- Ligeti, YN, Schein
  - JHEP 01 (2026) 095, 2506.21675

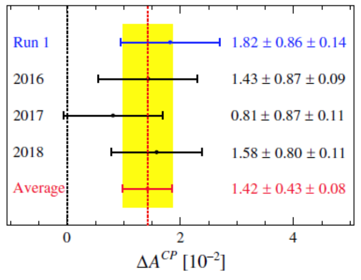
- Ligeti, Robinson
  - PRL 115 (2015) 251801, 1507.06671
- Jung
  - PRD 86 (2012) 053008, 1206.2050

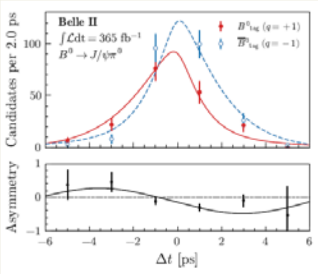
- Fleischer et al.
  - EPJC 86 (2026) 215, 2505.06102
  - JHEP 03 (2015) 145, 1412.6834

$B_q \to J/\psi\, P$: 16 observables

Process	B	A/C	S
$B^+ \to J/\psi\, \pi^+$	$(3.92 \pm 0.09) \times 10^{-5}$	$(+1.23 \pm 0.47) \times 10^{-2}$	$-$
$B^+ \to J/\psi\, K^+$	$(1.02 \pm 0.02) \times 10^{-3}$	$(+1.8 \pm 3.0) \times 10^{-3}$	$-$
$B_d \to J/\psi\, \pi^0$	$(1.74 \pm 0.07) \times 10^{-5}$	$(+8.5 \pm 8.5) \times 10^{-2}$	-0.87 ± 0.11
$B_d \to J/\psi\, K^0$	$(8.91 \pm 0.21) \times 10^{-4}$	$(+0.9 \pm 1.0) \times 10^{-2}$	$+0.708 \pm 0.012$
$B_s \to J/\psi\, \pi^0$	$< 1.21 \times 10^{-5}$	NA	NA
$B_s \to J/\psi\, K_S$	$(1.92 \pm 0.14) \times 10^{-5}$	-0.28 ± 0.42	-0.08 ± 0.41

- LHCb, 2411.12178
- Belle II, 2410.08622
- LHCb, 2402.05528
- Belle, 2311.12724





$B_q \to J/\psi\, P$: 12 parameters

- $A = \left(V_{cb}^* V_{cq}\right)\left(A_c^{(0)} + \varepsilon A_c^{(1)}\right) + \left(V_{ub}^* V_{uq}\right) A_u^{(0)}$
  - $SU(3)_F$ limit: $A_q^{(0)}$
  - $SU(3)_F$ breaking: $\varepsilon\, \mathrm{diag}(+1, +1, -2)$, $\varepsilon \sim 0.2$

- $SU(3)_F \Longrightarrow 5\ A_c^{(0)}, 4\ A_c^{(1)}, 3\ A_u^{(0)}$ relations

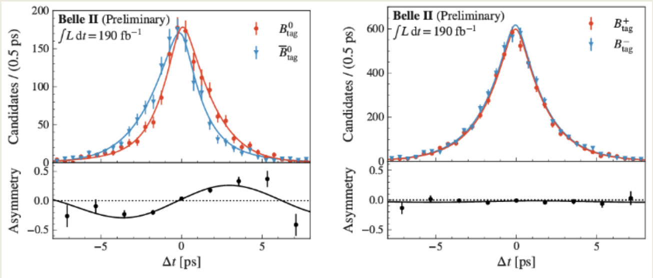
$\Longrightarrow$ 6 independent complex amplitudes:

- $1_{A_c^0} + 2_{A_c^1} + 3_{A_u^0}$

$B_q \to J/\psi\, P$: 4 relations

- 4 relations:
  - $A_{\psi K^+}/A_{\psi\pi^+} = -|V_{cd}/V_{cs}|^2$
    - $\Delta A_{CP} \Longrightarrow A_{\psi\pi^+} = (1.23 \pm 0.47) \times 10^{-2}$, $A_{\psi K^+} = (-6.5 \pm 2.5) \times 10^{-4}$
  - $C^d_{\psi K^0}/C^s_{\psi \bar{K}^0} = -|V_{cd}/V_{cs}|^2$
    - $\Longrightarrow C^s_{\psi\bar{K}^0} = -0.17 \pm 0.19$
  - $S^d_{\psi K_S} - s_{2\beta} = -|V_{cd}/V_{cs}|^2\, (c_{2\beta}/c_{2\beta_s})\, (S^s_{\psi K_S} + s_{2\beta_s})$
    - $\Longrightarrow S^d_{\psi K_S} - s_{2\beta} = +0.001 \pm 0.015$
  - $(1+\lambda^2) s_{2\beta} = S^d_{\psi K_S} - \lambda^2 S^d_{\psi\pi} - 2 c_{2\beta} t_\gamma (\Delta_K + \lambda^2 \Delta_\pi)$
    - $\Longrightarrow S^d_{\psi K_S} - s_{2\beta} = -0.05 \pm 0.03$

$\sin 2\beta = ?$



- Neglecting $\frac{V_{ub}V_{us}}{V_{tb}V_{ts}}\frac{P}{T}$ [good to $O(0.01)$]
  - $\sin 2\beta = S^d_{\psi K_S}$
- Neglecting $\varepsilon_{SU(3)}$ [good to $O(0.003)$]
  - $\sin 2\beta = S^d_{\psi K_S} + \left|\frac{V_{cd}}{V_{cs}}\right|^2 \frac{c_{2\beta}}{c_{2\beta_s}}\left(S^s_{\psi K_S} + s_{2\beta_s}\right)$
- Neglecting $\varepsilon^2_{SU(3)}$ [good to $O(0.001)$]
  - $\sin 2\beta = S^d_{\psi K_S} + \left|\frac{V_{cd}}{V_{cs}}\right|^2 \frac{c_{2\beta}}{c_{2\beta_s}}\left(S^s_{\psi K_S} + s_{2\beta_s}\right)$

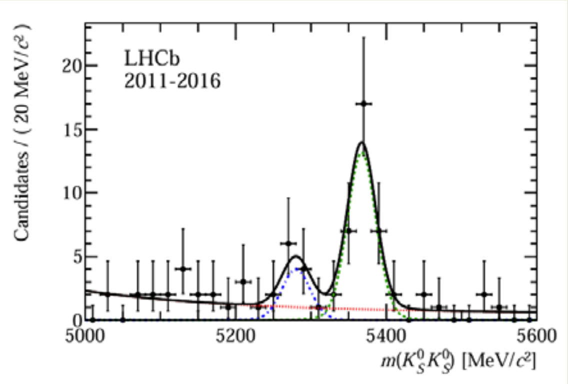
$$\times [1 + \frac{R^{sd}_{K^0\overline{K^0}} - 1}{2} + \frac{C^s_{\psi K_S} c_{2\beta_s}}{S^s_{\psi K_S}}(\varepsilon Im \frac{A_c^{(1)}}{A_c^{(0)}} - \rho(1+\bar{\lambda}^2)\frac{C^s_{\psi K_S}}{2\eta}]$$

$B_q \to J/\psi\, P$: Wishes

Process	$\boldsymbol{B}$	$\boldsymbol{A/C}$	$\boldsymbol{S}$
$B^+ \to J/\psi\, \pi^+$	$(3.92 \pm 0.09) \times 10^{-5}$	$(+1.23 \pm 0.47) \times 10^{-2}$	$-$
$B^+ \to J/\psi\, K^+$	$(1.02 \pm 0.02) \times 10^{-3}$	$(+1.8 \pm 3.0) \times 10^{-3}$	$-$
$B_d \to J/\psi\, \pi^0$	$(1.74 \pm 0.07) \times 10^{-5}$	$(+8.5 \pm 8.5) \times 10^{-2}$	-0.87 ± 0.11
$B_d \to J/\psi\, K^0$	$(8.91 \pm 0.21) \times 10^{-4}$	$(+0.9 \pm 1.0) \times 10^{-2}$	$+0.708 \pm 0.012$
$B_s \to J/\psi\, \pi^0$	$< 1.21 \times 10^{-5}$	NA	NA
$B_s \to J/\psi\, K_S$	$(1.92 \pm 0.14) \times 10^{-5}$	-0.28 ± 0.42	-0.08 ± 0.41

- **Measuring $\boldsymbol{S^s_{\psi K_S}, C^s_{\psi K_S}}$ will close in on $\boldsymbol{\sin 2\beta}$**

$B_s \to K^0\overline{K^0}$



- Amhis, Grossman, YN, JHEP02 (2023) 113, 2212.03874
- Grossman, Neubert, YN, Shpilman, Viernik, JHEP 05 (2025) 210, 2407.13506
- Observables:
  - $R_{KK}^{ss} \equiv \frac{\Gamma(B_s \to K^0\overline{K^0})}{\Gamma(B_s \to K^+K^-)}$
  - $A_{CP}(B_s \to K^+K^-) = S_{K^+K^-}^s \sin(\Delta m_s t) - C_{K^+K^-}^s \cos(\Delta m_s t)$
- Theory vs. experiment:
  - SM + isospin: $R_{KK}^{ss} - S_{K^+K^-}^s \cot\gamma = 1$
  - Experiment: $R_{KK}^{ss} - S_{K^+K^-}^s \cot\gamma = 0.58 \pm 0.13$

  $\Longrightarrow$ 3σ deviation
- Wish list:
  - **Branching ratios:**
    - $\boldsymbol{BR(B_{s,d} \to K^0\overline{K^0})}$
  - **CP asymmetries in $B_{s,d} \to K^0\overline{K^0}$:**
    - $\boldsymbol{S^s_{K^0\overline{K^0}}, C^s_{K^0\overline{K^0}}, S^d_{K^0\overline{K^0}}, C^d_{K^0\overline{K^0}}}$

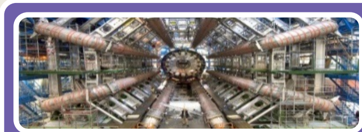
$B^{\pm} \to \pi^{\pm}\pi^{0}$

- Grossman, Ligeti, YN, work in progress
- CPV Observable:
  - $A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{0}) = \frac{\Gamma(B^{-}\to\pi^{-}\pi^{0})-\Gamma(B^{+}\to\pi^{+}\pi^{0})}{\Gamma(B^{-}\to\pi^{-}\pi^{0})+\Gamma(B^{+}\to\pi^{+}\pi^{0})}$
- Experiment:
  - $A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{0}) = -0.01 \pm 0.04$
- Theory:
  - $A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{0}) = 0$ in the "isospin limit", but
    - EWP
    - $\pi - \eta$ mixing
    - Isospin violation in strong penguins
    - $\Delta I = 5/2$

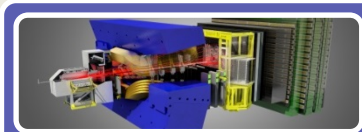
  $\Longrightarrow A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{0}) \sim \text{a few} \times 10^{-3}$
- Wish list:
  - Measure $\boldsymbol{A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{0})}$

CPV conclusions

Six decay processes, $B_q \to \psi P$ $(q = u, d, s; P = K, \pi)$ are related via SU(3)



6 decay rates + 10 CP asymmetries vs. 12 independent parameters $\Longrightarrow$ 4 predictions/tests of CPV



In particular, closing in on $\sin 2\beta - S^d_{\psi K_S}$

Measuring $S^s_{\psi K_S}, C^s_{\psi K_S}$ will be useful

$\Gamma(B_s \to K_S K_S)$ violates an isospin relation by 3σ;
Measuring $S^s_{K_S K_S}, S^d_{K_S K_S}$ will be useful

$A_{CP}(B^+ \to \pi^+ \pi^0)$ will provide insights on electroweak penguins and on isospin violation

Backup Slides

$B \to KK, K\pi$ - experimentally

Process	BR$\times 10^5$	S	C/A
$B_s \to K^0\overline{K^0}$	1.76 ± 0.31		
$B_s \to K^+K^-$	2.66 ± 0.22	$+0.139 \pm 0.032$	$+0.172 \pm 0.031$
$B_d \to K^0\overline{K^0}$	0.121 ± 0.016	-0.8 ± 0.4	0.0 ± 0.4
$B^+ \to K^0\pi^+$	2.37 ± 0.08	$-$	-0.017 ± 0.016
$B_d \to K^+\pi^-$	1.96 ± 0.05	$-$	-0.0834 ± 0.0032

$R_{KK}^{ss}/R_{\pi K}^{ud}$ - formalism

- $A(B_s \to K^0\overline{K^0}) = \frac{G_F}{\sqrt{2}}\lambda_p^s[\left(\alpha_4^p - \frac{1}{2}\alpha_{4,EW}^p\right)A_{K\overline{K}} + \left(b_3^p + b_4^p - \frac{1}{2}b_{3,EW}^p - \frac{1}{2}b_{4,EW}^p\right)B_{K\overline{K}} + \left(b_4^p - \frac{1}{2}b_{4,EW}^p\right)B_{\overline{K}K}]$
- $A(B_s \to K^+K^-) = \frac{G_F}{\sqrt{2}}\lambda_p^s[(\delta_{pu}\alpha_1 + \alpha_4^p + \alpha_{4,EW}^p)A_{K\overline{K}} + \left(b_3^p + b_4^p - \frac{1}{2}b_{3,EW}^p - \frac{1}{2}b_{4,EW}^p\right)B_{K\overline{K}} + (\delta_{pu}b_1 + b_4^p + b_{4,EW}^p)B_{\overline{K}K}]$
- $B_{KK}/A_{KK} \approx 0.0037$

R_{KK}^{ss} - Isospin

- $A(B_s \to K^0\overline{K^0}) = \frac{G_F}{\sqrt{2}}\lambda_p^s[\alpha_4^p A_{K\bar{K}}$
  $+(b_3^p + b_4^p)B_{K\bar{K}} + (b_4^p)B_{\bar{K}K}]$

- $A(B_s \to K^+K^-) = \frac{G_F}{\sqrt{2}}\lambda_p^s[(\delta_{pu}\alpha_1 + \alpha_4^p)A_{K\bar{K}}$
  $+ (b_3^p + b_4^p)B_{K\bar{K}} + (\delta_{pu}b_1 + b_4^p)B_{\bar{K}K}]$

First order in $R_{bs}^{ut} \equiv \left|\frac{V_{ub}V_{us}}{V_{tb}V_{ts}}\right| \simeq 0.02$

- The R ratios:
- $R_{KK}^{ss} = 1 + 2R_{bs}^{ut}\cos\gamma \times Re[(T+E)/(P+P_A)]$
- $R_{\pi K}^{ud} = 1 + 2R_{bs}^{ut}\cos\gamma \times Re[(T-A)/P]$
- $R_{KK}^{sd} = 1$

- The CP asymmetries:
- $C_{K^+K^-}^{s} = 2R_{bs}^{ut}\sin\gamma \times Im[(T+E)/(P+P_A)]$
- $S_{K^+K^-}^{s} = 2R_{bs}^{ut}\sin\gamma \times Re[(T+E)/(P+P_A)]$